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DIFFERENT CLASSES OF SOLAR AND SOLAR-TERRESTRIAL EVENTS IN RELATION TO THE PHASE OF THE SOLAR CYCLE

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ABSTRACT. The frequency of occurrence of solar and solar-terrestrial events in relation to the phase of the solar cycle has been studied for the period 1956–63. The events include sunspot, Ca-plage, solar flare, solar radio burst at metre wavelengths, geomagnetic storm and short wave fadeout. Each event has been classified into four different groups—*viz*., small, moderate, large and outstanding depending on its degree of activity. It has been found that solar and solar-terrestrial phenomena show maximum correlation with sun-spot cycle when considered as a whole (without classification) as also for small, moderate and large magnitudes of their activities. Outstanding events of all types tend to occur during the ascending and descending phases of the solar cycle, avoiding the peak phase.

INTRODUCTION

It is now well established that all sorts of solar and solar-terrestrial events are very closely associated with one feature, viz. the sunspot whose number or area actually determines the progress of the solar cycle. Thus when sunspots are numerous, all the different types of solar and associated geophysical phenomena will be more frequent. The frequency of occurrence of all these events follow closely the solar cycle.

Nevertheless, it appears from the analysis of Newton and Milsom (1954) that very big geomagnetic storms occur more frequently few years on either side of the peak phase of the corresponding solar cycle. This behaviour is exhibited by 17 storms of outstanding intensity (average ranges $2^{\circ}\cdot4$ in D 1180γ in H and 790γ in Z) collected from nine sunspot cycles beginning with the minimum at 1856. However, this peculiar characteristics of avoiding the peak phase was not observed in the case of the distribution of giant sunspots (mean area $\geqslant$ 1500 millionths of the solar disk) and outstanding solar flares (class 3+).

Again, Kodama (1961) observed that unusual increases in cosmic rays and fast type of polar cap absorption (PCA) events occur only during the ascending and descending phases of the solar cycle avoiding the maximum phase. On the contrary, small increases in cosmic rays and slow type of PCA events were found by him to be concentrated more around the peak period of sunspot cycle. Dependence of the fast type of PCA events as also ground level enhancement (GLE) of cosmic rays on the phase of the solar cycle can also be inferred from the investigations of Warwick and Haurwitz (1962). They concluded that during the peak solar activity high energy protons rarely reach the earth whilst those producing PCA events suffer maximum delay. It is known that unusual increase in cosmic rays detected on the surface of the earth are almost alwsays associated with highly intense solar eruptions. This led Takakura and Ono (1961) to investigate whether outstanding solar eruptions responsible for cosmic ray increases on the surface of the earth are also absent during the peak period of solar activity or the effect is due to some other reason unfavourable for accelerating particles. Solar flares of importance 3+ and unusually intense radio outbursts on centimetric waves ($>5\times10^3$ flux units for 2800 Mc/s and $>10^4$ flux units for 3750 and 9400 Mc/s) were considered by them for detecting intense solar eruptions. It was found that intense outbursts on centimetric waves occur in the ascending and descending phases of the solar cycle avoiding the peak phase while the frequency of occurrence of weaker bursts is maximum at the maximum period of the solar cycle. On the contrary, the distribution of frequency of ocurrence of class 3+ flares as also flares of lower classes follow the sunspot cycle quite closely being most frequent during the peak phase and then decreasing away from it. Japanese workers mentioned above, attributed this peculiar behaviour of the outstanding solar terrestrial events to be exclusively a solar effect. On the contrary, Warwick and Haurwitz suggested that the phenomena as observed by them might be possibly due to the effect of stronger interplanetary magnetic field and high degrees of disorder therein on the movement of particles during the peak phase of the solar activity.

Recently the problem was examined by the present authors (Das Gupta and Basu, 1965) with respect to various other solar and solar-terrestrial events. The former include sunspots, calcium plages, solar flares and metre wave radio bursts (200 Mc/s) while the solar-terrestrial events include short wave radio fadeouts and geomagnetic storms. They found that outstanding classes of all solar and solar-terrestrial events mentioned above mostly tend to avoid the peak phase of solar activity and occur more frequently during the ascending and descending phases. It was concluded by them that the effect in general must be of solar origin rather than any modulation effect in the sun-earth space. It is the purpose of the present paper to describe the details of the work referred to above.

METHOD OF ANALYSIS

As has already been mentioned in the previous section, the present analysis has been carried out for events which include sunspots, calcium plages, solar flares, solar radio bursts at 200 Mc/s, short wave radio fadeouts and geomagnetic storms. The period covered is 1956 to 1963 for which fairly continuous data for all these events are available.

Each of the individual events mentioned above was divided into four classes—small, moderate, large and outstanding—depending on the magnitude of its activity. Thus it is known that activities of sunspots and calcium plages depend on their areas on the solar disk—big centres of activities being formed around large sunspot groups and huge calcium plages. These have therefore been classified according to their areas. Flares of even class 3+ were found by Newton and Milsom as well as Takakura and Ono to obey the sunspot cycle more or less satisfactorily. It was, however, indicated by the latter group that the energy associated with certain 3+ flares might be greater than that for others of the same class. As such $H\alpha$ line width, also recognised as an index for the intensity of solar flares, was taken as the basis of classification in our analysis. So far as solar radio noise burst at metre wavelength is concerned, the peak flux density in units of watts/sq·metre/cycles per second is the best index for measurement. In the case of short wave radio fadeout, however, the duration of each event, known to vary directly with the intensity of the event, has been considered for the classification. Lastly, the internationally adopted K index has been taken as a measure of the intensity of geomagnetic storms. The criteria of different classifications are shown in Table I.

TABLE I

Criteria of classification of different solar and solar-terrestrial events

Name of events	Properties to be studied	Unit of measurement	Classifications			
			Small	Moderate	Large	Out-standing
Sunspot group	Area at CMP	$\times 10^{-6} \times$ Area of solar disk.	<500	500–<1000	1000–<2000	$\geqslant 2000$
Calcium plage.	Area at CMP	$\times 10^{-6} \times$ Area of solar disk.	<1000	1000–<5000	5000–<10000	>10000
Solar flare	$H\alpha$ line width	Angstrom unit	<5	5–<10	10–<15	>15
Solar radio brust.	Peak flux density.	$\times 10^{-22}$ W/M^2/CPS.	<500	500–<1000	1000–<5000	$\geqslant 5000$
Short wave fadeout.	Duration	Minutes	<50	50–<100	100–<200	$\geqslant 200$
Geomagnetic storm.	Value of K index.	IAGA classification	$\leqslant 5$	6–7	8	9

Every individual year of the period 1956-63 was divided into two six monthly intervals. The total number of every event, irrespective of classes, occurring during each of these six monthly intervals was first determined for the entire period and histograms were drawn. These are shown in Fig. 1 which also includes six monthly means of final Zurich sunspot numbers. The number of occurrences of each of the different classes for every event were then counted individually for the six monthly intervals over the entire period and the respective histograms, drawn (Figs. 2). From Figs. 1 and 2, the particular half-yearly intervals showing maximum activity determined by number of occurrences of the different classes as also the total number (irrespective of classes) of each event were obtained.

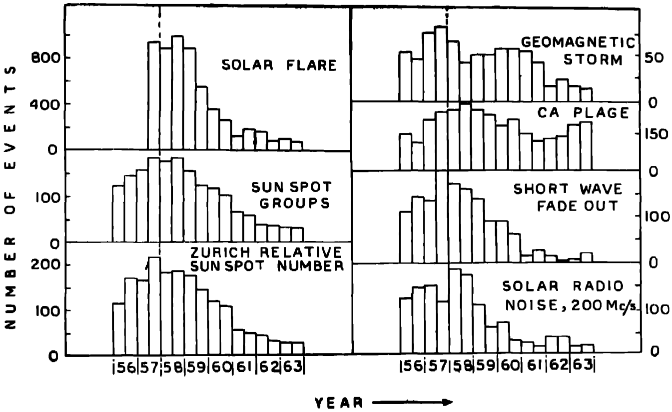

Fig. 1. Variations of the total number of various solar and solar-terrestrial events in course of a solar cycle.

The results are shown in Table II. Correlation coefficients were also determined for each case with respect to corresponding half yearly mean sunspot numbers. These are shown in Table III.

RESULTS

Results obtained in the present analysis are shown in Figs. 1 and 2 and in Tables II and III. It will be found from Fig. 1 that the half-yearly variations from 1956-1963 of the total number of different events (without classification) take place more or less in accordance with that of sunspot number for the same period. The association with sunspot numbers appears to be very prominent for the events sunspot groups, solar flares, solar radio noise bursts and short wave fade outs the frequency of occurrence falling gradually on either side of the peak period indicated by the dotted line. In case of calcium plages and geomagnetic storms, however, the decrease in frequency of occurrence, as one proceeds away from the peak period, is not so uniform as is expected from sunspot numbers.

Fig. 2 shows the half-yearly intervals indicating the maximum number of occurrences of different classes of each event which have been indicated in Table II. It has been found that all types of solar and solar-terrestrial events considered here and belonging to the outstanding class occur most frequently either in the ascending or in the descending phase or in both of these phases of the solar cycle,

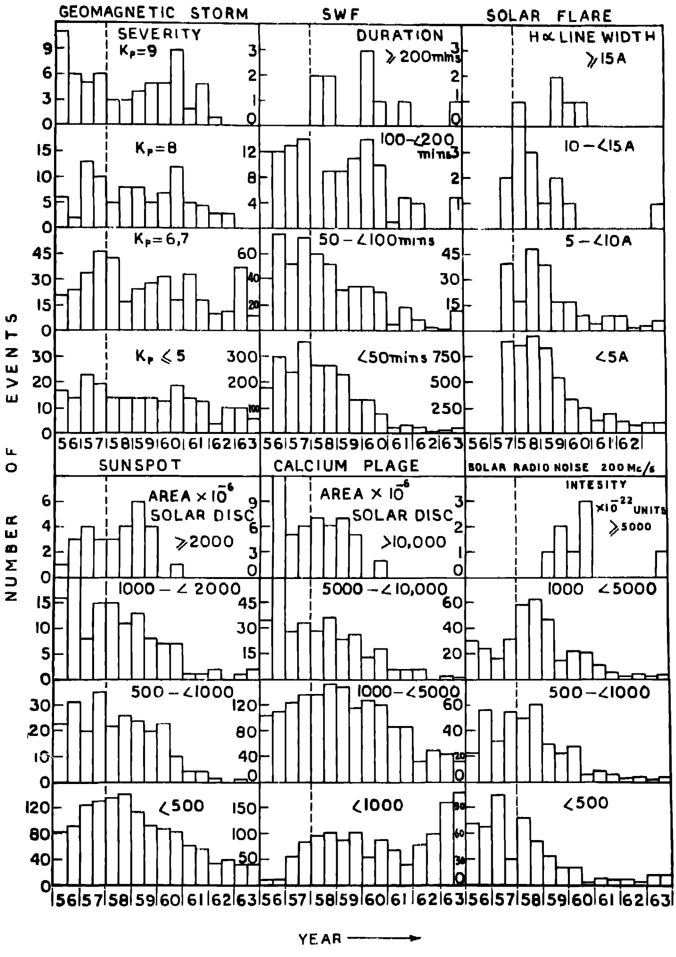

Fig. 2. Variations of different classes of solar and solar-terrestrial events in course of a solar cycle.

TABLE II

Years showing maximum occurrences of different classes of solar and solar-terrestrial events in relation to the phase of the solar cycle.

Events→	Sunspot Group			Ca Plage			Solar Flare		
Classes	Ascending	Peak	Descending	Ascending	Peak	Descending	Ascending	Peak	Descending
Small	—	1958 (II)	. .	—	1958 (II)	1963 (II)	—	1958 (II)	—
Moderate	—	1957 (II)	—	—	1958 (II)	—	—	1958 (II)	—
Large	1956 (II)	—	—	1956 (II)	-	—	—	1958 (I)	-
Outstanding	—	—	1959 (I)	1956 (I, II)	—	—	—	—	1959 (II)
Total number of Events	—	1957 (II)	—	—	1958 (II)	—	—	1958 (II)	—

Events→	Solar Radio Burst			Short Wave Fadeout			Geomagnetic Storm		
Classes ↓	Ascending	Peak	Descending	Ascending	Peak	Descending	Ascending	Peak	Descending
Small	—	1957 (I)	—	.	1957 (II)	—	—	1957 (I)	—
Moderate	—	1958 (II)	—	1956 (II)	1957 (II)	—	—	1957 (II)	—
Large	—	1958 (II)	—	—	1957 (II)	1960 (I)	—	1957 (I)	1960 (II)
Outstanding	—	—	1960 (II)	—	-	1960 (I)	1956 (I)	—	1960 (II)
Total number of Events	—	1958 (I)	—	—	1957 (II)	—	—	1957 (II)	—

Note : (1) Ascending phase : 1954-56, Peak Phase : 1957-58 and Descending phase : 1959-63

(2) Suffix (I) indicates first half of the year (January to June), suffix (II) indicates second half (July to December).

TABLE III

Correlation coefficients between half-yearly mean sunspot number and number of occurrences for different classes of various events

Classes	Correlation coefficients for events					
	Sunspot group	Calcium Plage	Solar flare	Solar Radio burst	SWF	Geomagnetic storm
Small	0.9560	0.3534	0.7381	0.6337	0.9587	0.6030
Moderate	0.9358	0.6017	0.6475	0.9005	0.9001	0.4836
Large	0.8321	0.8021	0.6058	0.7861	0.7985	0.5309
Outstanding	0.5548	0.4844	0.2892	−0.2655	−0.2547	0.4134
Total	0.9861	0.6751	0.7378	0.8684	0.9767	0.7471

avoiding the peak phase. The same tendency is also clearly shown by large sunspots and calcium plages. But for all other events, large, intermediate and small classes follow the solar cycle more or less closely-- the number of occurrences in each of these cases being maximum during the peak phase of solar activity. It is found (Table III) that the correlation coefficient with sunspot numbers is least for the outstanding class of all events while it has highest value when total number of events are considered

DISCUSSION

It was shown by previous workers, as has already been mentioned, that unusually high incidents of cosmic ray increase, polar cap absorption and radio outbursts at centimetre wavelengths occur less frequently during the sunspot maximum period. The present analysis shows that outstanding events of sunspot, calcium plage, solar flare, radio outburst at metre wavelengths, short wave radio fadeout and geomagnetic storm tend to concentrate themselves more towards periods of moderate activity. It may be noted that, of these various events' visible solar flare, radio outbursts at all wavelengths and short wave fadeout involves wave radiation of wide range of frequencies from the sun while cosmic ray increase, polar cap absorption and geomagnetic storms recorded on the earth indicate particle radiation therefrom, of various energies. On the other hand, sunspots and calcium plages represent centres of activity on the solar surface. It thus appears that all the outstanding solar and solar-terrestrial events due to both wave and particle radiation from the sun as also centres of activity occur most frequently during the ascending and descending phases of the solar cycle, avoiding the peak phase.

It was indicated by Kodama that solar protons responsible for unusual increase in cosmic rays and fast type PCA are accelerated simultaneously in the same region of the solar atmosphere from where centimetre wave radio outbursts are also produced. This is the reason, according to him, why these three phenomena, exhibit the same effect of avoiding the maximum period of solar activity. Takakura and Ono, however, suggested that during the peak phase the frequency of disturbance in the solar atmosphere being very high, the time interval between successive triggering actions is too short for much energy to be stored to cause most intense erruptions. During moderate activity, triggers being less frequent outstanding events may occur in the sun due to the possibility of storage of more energy. Thus the Japanese workers investigating on cosmic ray, PCA, and microwave outbursts maintain the view, as was indicated earlier, that this rather peculiar behaviour of the outstanding events of avoiding the peak period of solar activity is exclusively a solar effect. On the other hand, Warwick and Haurwitz working only with cosmic ray and PCA events suggested that the disordered interplanetary magnetic field during the maximum phase might be responsible for preventing particles from reaching the earth. Since it is now evident that the characteristic effect is exhibited by both wave as well as particle radiations from the sun and it being known that the interplanetary magnetic field can have no effect on wave radiation, it is clear that the origin of the peculiar phenomenon is the solar atmosphere itself rather than the sun-earth space. Furthermore, the same phenomenon being shown also by sunspots and calcium plages, it can be concluded that somehow the highly disturbed sun and its atmosphere prevent the formation of very large so-called 'centres of activity' and hence the occurrence of any outstanding event during the peak phases of solar cycles.

Investigations by previous workers showed that unusual events of cosmic ray increase, polar cap absorption and microwave outbursts are concentrated either in the first half of 1956 or in the second half of 1960 or in both. It is found from Fig. 2 and Table II of the present analysis that outstanding occurrence of calcium plage, geomagnetic storms and metre wave radio outburst from the sun have also got the tendency of predominating at the same periods. On the other hand corresponding events of sunspot groups and solar flares are more frequent at the first and second halves of 1959 respectively while those for short wave fadeout are most predominant at the first half of 1960. However, as the international data giving H_α line width of solar flares are insufficient prior to July 1957, it is difficult to assess the situation of intense solar flares at that period. It is rather interesting to note that big flares do not correspond to big spots and plages. It therefore appears that outstanding events of solar flares, sunspots and calcium plages occur more or less independently of each other.

CONCLUSION

It may thus be concluded that solar and solar-terrestrial phenomena show maximum correlation with the sunspot cycle when taken as a whole as well as for small, moderate and large magnitudes of their activities. All sorts of outstanding solar and solar-terrestrial events tend to occur during the ascending and descending phases of the solar cycle, avoiding the maximum phase. Since the same tendency is exhibited by both wave as well as particle phenomena including sunspots and calcium plages, the effect must be of solar origin. It appears that unusually intense centres of activity are much easier to be formed in the solar atmosphere during the period of moderate activity than that during the maximum phase. Outstanding flares are not necessarily associated with outstanding spots or plages.

It should, however, be noted that the present analysis has been carried out over part of one solar cycle for which data are available. Studies of data over several solar cycles in future will be interesting and will establish firmly the phenomenon obtained in this analysis which will definitely reveal many new facts on solar physics in general and on the formation of centres activity in particular.

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